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Corn Stover Impacts on Near-Surface Soil Properties of No-Till Corn in Ohio

Humberto Blanco-Canqui,* R. Lal, W. M. Post, R. C. Izaurralde, and L. B. Owens

ABSTRACT

Corn (*Zea mays* L.) stover is a primary biofuel feedstock and its expanded use could help reduce reliance on fossil fuels and net CO_2 emissions. Excessive stover removal may, however, negatively impact near-surface soil properties within a short period after removal. We assessed changes in soil crust strength, bulk density (ρ_b), and water content over a 1-yr period following a systematic removal or addition of stover from three no-till soils under corn in Ohio. Soils from ongoing experiments at the North Appalachian Experimental Watershed (NAEW), Western Agricultural Experiment Station (WAES), and Northwestern Agricultural Experiment Station (NWAES) of Ohio Agricultural Research and Development Center (OARDC) were studied. Six stover treatments of 0 (T0), 25 (T25), 50 (T50), 75 (T75), 100 (T100), and 200 (T200)% were imposed on 3 by 3 m plots corresponding to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1} of stover, respectively. Cone index (CI), shear strength (SHEAR), ρ_b, and volumetric water content (θ_v) were measured monthly from June through December 2004 and in May 2005. Effects of stover removal on increasing CI and SHEAR were soil-specific. Stover removal consistently increased ρ_b and decreased θ_v across soils ($P < 0.01$). Compared with the normal stover treatment (T100), doubling the amount of stover (T200) did not significantly affect soil properties except θ_v where, after 1 yr, T200 increased θ_v by 1.3 to 1.6 times compared with T100 across all sites ($P < 0.05$). After 1 yr, complete stover removal (T0) increased CI by 1.4 times and SHEAR by 1.3 times at NAEW compared with T100 and T75, but CI increases at other sites were nonsignificant. At NWAES, T0 increased SHEAR by 26% compared with T100 ($P < 0.05$). The T0 decreased θ_v by two to four times except in winter months and increased ρ_b by about 10% compared with T100 ($P < 0.05$). In a short-term test, stover removal resulted in increased soil crust strength and reduced soil water content.

Corn stover is a potential feedstock source for biofuel production that may reduce dependence on fossil fuels and net CO_2 emissions (Wilhelm et al., 2004). Technologies for the conversion of this high-cellulose feedstock into biofuel (i.e., ethanol) are well advanced although corn stover harvesting for this purpose is not a routine practice (Johnson et al., 2004). Removal of corn stover, however, reduces the quantity of residue mulch left on the soil surface and can negatively impact soil physical, hydrological, biological, and thermal properties as well as increase soil erosion.

H. Blanco-Canqui and R. Lal, Carbon Management and Sequestration Center, FAES/OARDC, School of Natural Resources, The Ohio State Univ., 2021 Coffey Rd., Columbus, OH 43210-1085; W.M. Post, Environmental Sci. Div., Oak Ridge National Lab., Oak Ridge, TN 37831; R.C. Izaurralde, Joint Global Change Research Institute, 8400 Baltimore Ave., Suite 201, College Park, MD 20740-2496; L.B. Owens, USDA-ARS, North Appalachian Experimental Watersheds, P.O. Box 488, Coshocton, OH 43812. Received 2 May 2005. *Corresponding author (blanco.16@osu.edu).

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Excessive removal of corn stover can induce rapid changes particularly in soil surface conditions. It can increase the susceptibility of the surface soil to crusting through increased surface sealing, rainfall-induced consolidation, and abrupt wetting and drying (Or and Ghezzehei, 2002). Corn stover mulch intercepts raindrops responsible for crust-forming processes such as detachment of soil particles and dispersion of surface aggregates. Crusts are thin soil surface layers about 5 cm thick only (USDA-NRCS, 1996), but they are denser and less permeable than the underlying soil layers (Busscher and Bauer, 2003). Because of their high strength and low permeability, crusts can modify the soil surface processes, restricting seedling emergence (Baumhardt et al., 2004), reducing water infiltration and aeration (Wells et al., 2003), and increasing surface runoff (Bajracharya and Lal, 1998). Thus, increased crust strength as a result of stover removal can have detrimental effects principally on plant growth (Maiorana et al., 2001). Stover mulch also reduces the abrupt fluctuations in soil water regimes (Black, 1973a). Soils with stover mulch often have higher water content than those without mulch (Shaver et al., 2002). Soil water content is the single most important factor essential to plant growth, heat exchange, and other vital soil processes.

In some ecosystems, a partial removal of corn stover for energy production and other purposes may be a viable option without significantly affecting soil susceptibility to crusting or altering water regimes. Site-specific information on the threshold rates of corn stover removal is, however, needed to maintain soil physical and mechanical quality. Some studies have estimated that about 30% (Nelson, 2002), 40% (Kim and Dale, 2004), and 58% (Lindstrom et al., 1979) of the total corn stover production in the U.S. Corn Belt region may be available for biofuel production. These removal rates are, however, based mainly on the residue requirements to reduce soil erosion risks and not on the needs to moderate soil surface strength or soil C sequestration. Allowable removal rates of corn stover based on the needs to reduce soil erosion in the U.S. Corn Belt region are site-specific (Lindstrom et al., 1979; Nelson, 2002; Kim and Dale, 2004). Thus, the quantity of stover that must be retained on the soil to reduce crusting is also likely to depend on site-specific conditions such as tillage and cropping system (Kladivko, 1994), duration of management (Karlen et al., 1994), soil type (Gupta et al., 1987), agro-ecosystem and climate (Salinas-Garcia et al., 2001). Knowledge of the threshold levels of stover removal in relation to soil crust strength and water storage is

Abbreviations: CI, cone index; NAEW, North Appalachian Experimental Watersheds; NT, no-till; NWAES, Northwestern Agricultural Experiment Station; SHEAR, shear strength; WAES, Western Agricultural Experiment Station; θ_v, volumetric water content; θ_g, gravimetric water content; ρ_b, bulk density.

urgently needed to design stover management options for biofuel production while maintaining soil physical quality, reducing risks of pollution of surface water, and sustaining agricultural productivity.

While studies on the interacting effects of traditional tillage systems vs. residue management on soil strength properties are many (Larson et al., 1978; Lindstrom et al., 1979; Kladivko, 1994), changes in crust strength parameters and water content regimes resulting from differential corn stover retention in NT systems are not well documented. Moreover, the magnitude of the impacts of crop residue removal on soil crust strength properties can be variable depending on soil textural characteristics and management (Morachan et al., 1972; Black, 1973b; Gupta et al., 1987; Karlen et al., 1994; Shaver et al., 2002). Thierfelder et al. (2005) showed that CI of crusted soils without vegetative cover was seven times higher than that of those with vegetative cover. In contrast, Karlen et al. (1994) observed that differences in CI and ρ_b of soils within the surface 5-cm depth after 10 yr of complete removal and double addition of stover mulch annually under NT continuous corn were not significant in Rozetta and Palsgrove silt loams. These studies underscore the need of quantifying the effects of a systematic removal of corn stover in NT systems on soil surface strength. Experimental data on the response of near-surface soil strength properties to varying quantities of stover removal in NT systems for the eastern U.S. Corn Belt region targeted for stover harvesting are needed. Information relating stover removal across different soils can assist in better stover management decisions for biofuel production and soil quality improvement.

We hypothesized that corn stover removal or addition could induce rapid changes in soil crust strength parameters and water content, but the magnitude of impact of stover removal would vary with soil. Thus, the objective of this study was to assess the impact of different levels of corn stover on soil crust strength and water content over the short period of 1 yr for three Ohio soils under NT continuous corn management.

MATERIALS AND METHODS

Study Site and Management Descriptions

The present residue management study was superimposed on a long-term experiment located at three sites in Ohio. The project was initiated in May 2004 to characterize the effects of corn stover removal on physical quality, thermal properties, crop yield, and soil organic carbon (SOC) content for NT continuous corn systems. The three Ohio experimental sites include: (i) USDA-ARS North Appalachian Experimental Watersheds (NAEW) near Coshocton at the Ohio Agricultural Research and Development Center (OARDC), (ii) Western Agricultural Experiment Station (WAES) near South Charleston, and (iii) Northwestern Agricultural Experiment Station (NWAES) near Hoytville (Fig. 1). The WAES and NWAES are branches of the OARDC, the Ohio State University. The experimental sites extend over three contrasting soil series: Rayne silt loam (fine loamy, mixed, mesic Typic Hapludults) at NAEW, Celina silt loam (fine, mixed, active, mesic Aquic Hapludalfs) at WAES, and Hoytville clay loam (fine, illitic, mesic Mollic Epiaqualfs) at NWAES. The soils at

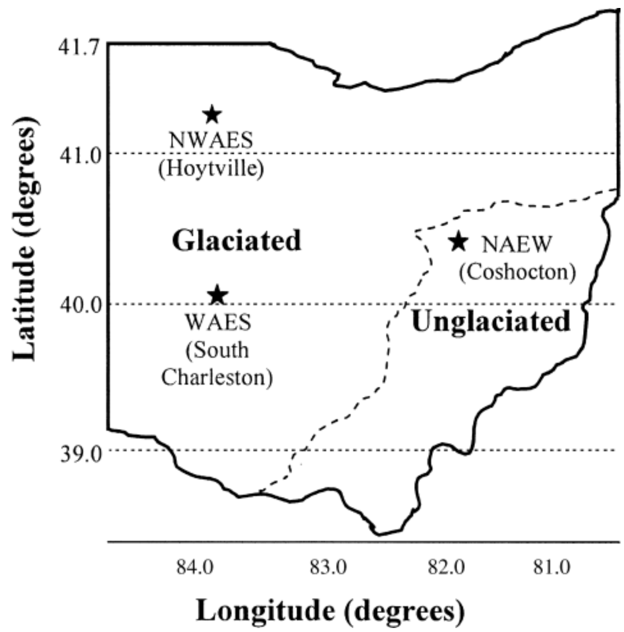

Fig. 1. Map of Ohio showing the locations of the three study sites: (1) North Appalachian Experimental Watersheds (NAEW) near Coshocton, (2) Western Agricultural Experiment Station (WAES) near South Charleston, and (3) Northwestern Agricultural Experiment Station (NWAES) near Hoytville in Ohio.

the NAEW site are unglaciated, well drained, and have moderate permeability with a slope of about 10%, whereas those at the NWAES and WAES sites are glaciated and very deep with a slope <2%. Soils at NWAES are very poorly drained with clay content two times higher than that at WAES and three times higher than at NAEW.

The experimental design at each site is a randomized complete block with six treatments replicated three times for a total of 18 plots measuring 3 by 3 m. The six treatments consisted of applying 0, 25, 50, 75, 100, and 200% of corn stover of the previous year, which at the start of the experiment in May 2004 corresponded to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha^{-1} of stover, respectively. The percentage of stover mulch cover in each plot was estimated using the line-transect method (Sloneker and Moldenhauer, 1977). Each plot was planted to corn in mid May 2004 and then any stover shifted during planting was redistributed to the corresponding plots. Each plot comprises four rows of corn spaced 0.75 m apart. Corn stover produced at the end of the growing season in October 2004 was redistributed immediately following harvest in the corresponding treatments. The six mulching rates at 0, 25, 50, 75, 100, and 200% are hereafter referred to as T0, T25, T50, T75, T100, and T200.

Determination of Cone Index and Shear Strength

Soil penetration resistance and SHEAR determinations were used as sensitive measures of soil crust strength (Kladivko, 1994; Silva et al., 2004). Because soil crusts are often <5 cm thick (USDA-NRCS, 1996), crust strength properties were measured within the surface 5-cm soil depth. Unlike some of the previous studies that often used small crust samples for strength determinations, the in situ crust strength measurements across the upper few centimeters of soil surface, in this study, may more closely integrate the vertical and lateral soil pressures against the surface soil structural crusts and simulate conditions encountered by corn seedlings during emergence. Accounting for the integrated strength of both surface crusts and the immediate underlying soils corresponding to the corn planting depth (4–6cm) is important to seedling emergence or crop establishment.

Soil penetration resistance and SHEAR were determined at each plot once a month from June through December 2004, and in May 2005. A static hand cone penetrometer (Eijkelkamp, Giesbeek, The Netherlands) was used for the measurements of soil penetration resistance (Lowery and Morrison, 2002). The penetrometer was pushed vertically downward at a constant speed of about 1 cm s^{-1}. The penetration depth of the cone for each measurement was 4 cm. Measurements were made in triplicate for the surface layer. The CI was computed by dividing the manometer reading (N) of the penetrometer by the base area (cm^2) of the penetrometer cone, and then the units were converted into MPa. The in situ shear strength was measured using a CL-612 shear vane tester (ELE International, Inc. Lake Bluff, IL; Serota and Jangle, 1972). The tester had a vane diameter of 1.9 cm and a 15.2-cm long spindle coupled to a torque meter. The SHEAR was measured by pushing the vane into the soil to a depth of 3 cm and turning the torque meter clockwise by hand at about 0.2 cm s^{-1} until the soil sheared. The readings of shear strength from the torque meter were obtained in units of kPa. Three measurements of CI and SHEAR were made at three random points in each plot to account for the high variability in these properties.

Soil Sampling and Laboratory Measurements

Intact soil cores (6 cm deep and 5.3 cm in diameter) were taken at the time of CI and SHEAR measurements for soil water content and ρ_b determinations. A double-cylinder hammer-driven sampler was used to collect soil cores manually. Samples were sealed in plastic bags, transported to the laboratory, and water content determined gravimetrically (Topp and Ferré, 2002). The ρ_b was determined using the core method (Grossman and Reinsch, 2002). The θ_v was computed based on the gravimetric water content (θ_g) and ρ_b data. To minimize soil disturbance effects of earlier monthly determinations of CI, SHEAR, ρ_b, and θ_g on later determinations, in situ measurements and soil sampling were made systematically at distinct points in a row along the interrow positions of each plot.

Statistical Analysis

Because the treatment × site and treatment × sampling date interactions were highly significant, one-factor ANOVA model was used to test whether differences in CI, SHEAR, ρ_b, and θ_v among the different stover mulch treatments were significant by site and sampling date. The GLM procedure was employed using SAS (SAS Institute, 1999). Comparison among treatments was performed using LSD at the 0.05 probability level. Simple regression models were fitted to establish functional relationships of CI, SHEAR, ρ_b, and θ_v with the different rates of stover cover. Changes in CI and SHEAR as a function of ρ_b were studied for each site.

RESULTS AND DISCUSSION

Crust Strength Parameters

Dependence of Cone Index and Shear Strength on Soil Water Content

Measured CI and SHEAR values were plotted against the θ_g to determine functional dependence relationships across the three sites (Fig. 2). Exponential equations provided the best fits between the crust strength parameters vs. θ_g for all the data points as shown in Eq. [1] and [2]. The coefficients of determination for the fitted Eq. [1] and [2] were highly significant because the number of observations was large (n = 432).

$$\mathrm{CI} = 3.435\exp(-3.745\theta_g)\ (n = 432,\ r^2 = 0.70, P < 0.001) \qquad [1]$$

$$\mathrm{SHEAR} = 84.00\exp(-2.455\theta_g)\ (n = 432,\ r^2 = 0.66, P < 0.001) \qquad [2]$$

These equations show that variations in θ_g explained 70% of the variability in CI and 66% in SHEAR ($P <$ 0.001), indicating that CI and SHEAR were highly dependent on θ_g. The Eq. [1] and [2] also show that CI and SHEAR were inversely related to θ_g, decreasing consistently with an increase in θ_g. The exponential relationships agree with Ohu et al. (1988) and Busscher and Bauer (2003) who observed that CI decreased exponentially with increasing θ_g on a clay, loamy sand, and sandy loam. The high dependence of CI and SHEAR on θ_g has been widely recognized (Sojka et al., 2001; Busscher and Bauer, 2003). Changes in soil-water content control processes including cohesion, friction, and normal stress within the soil structural crusts. Increase in θ_g generates positive pore water pressures, which separates the adjoining soil particles, reducing the cohesion and friction and overall CI and SHEAR (To and Kay, 2005).

Adjustment of Cone Index and Shear Strength

Soil crust strength parameters were adjusted to a common value of soil gravimetric water content (θ_{gc}) to reduce the confounding effect on CI and SHEAR of the measured θ_g. The CI and SHEAR measured at the NAEW and NWAES sites in November and December were not adjusted for θ_g effects because differences in θ_g in these months were not significant. Several empirical and conceptual models were studied to find the best corrective model based on our data. Previous research has shown that a unique corrective approach to eliminate the dependence of CI and SHEAR on θ_g across all soils does not exist. Approaches based on covariate models (Yasin et al., 1993), Taylor series (Busscher et al., 1997), and ratios of best-fit equations of strength parameters vs. θ_g (Busscher and Bauer, 2003) were tested. Some approaches did not significantly reduce the apparent and large effects of θ_g on the strength parameters. The best corrective approach for our data was the ratio of equations based on the exponential functions in Eq. [1] and [2] as

$$\text{Adjusted CI} = \text{Unadjusted CI} \times 3.435\exp[-3.745\ (\theta_{gc} - \theta_g)] \qquad [3]$$

$$\text{Adjusted SHEAR} = \text{Unadjusted SHEAR} \times 84.00\exp[-2.455\ (\theta_{gc} - \theta_g)] \qquad [4]$$

Procedures for taking the ratio of the exponential equations were those used by Busscher and Bauer (2003). The same Eq. [1] and [2] were used for the adjustment across all treatments and sites to ensure a uniform correction (W.J. Busscher, personal communication, 2005).

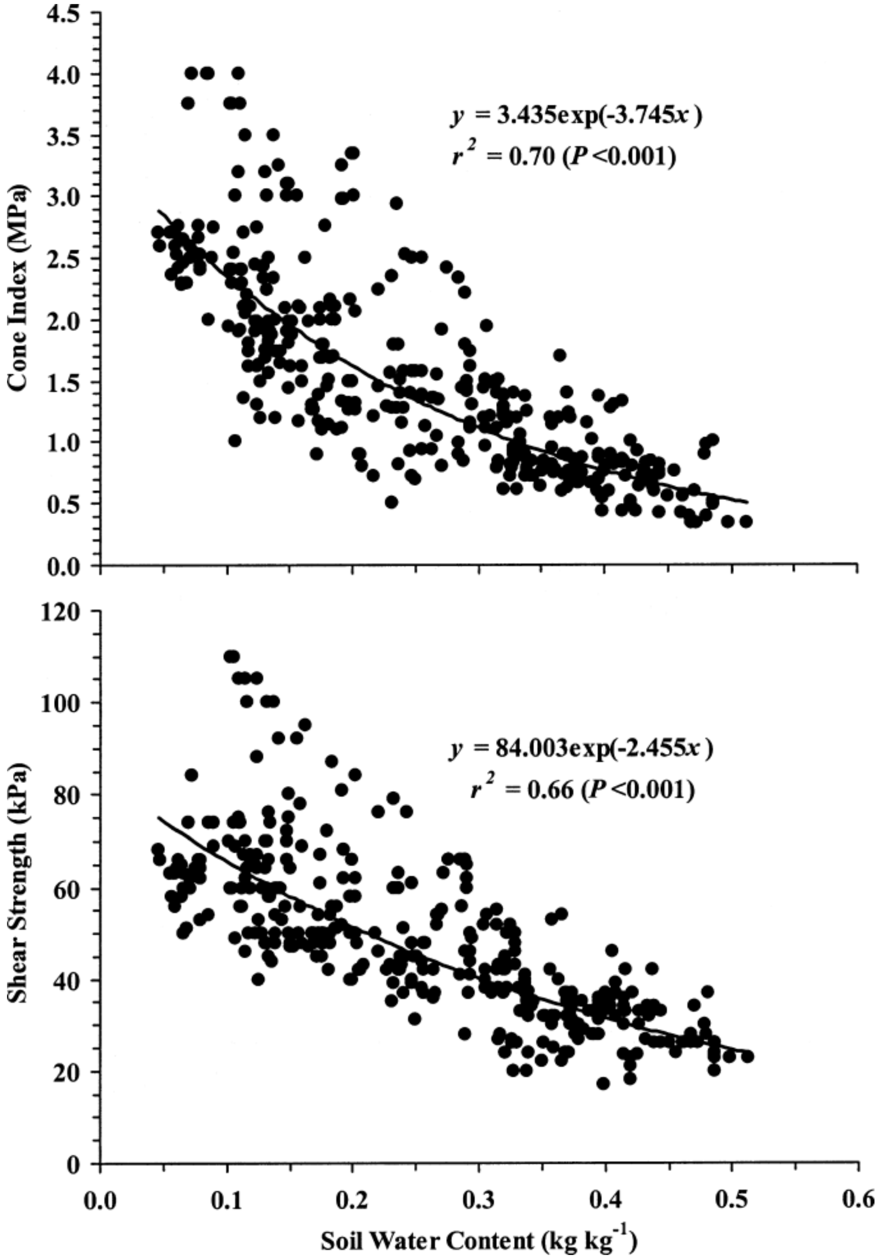

Fig. 2. Relationship of unadjusted data of cone index and shear strength with gravimetric water content for all data points across the three study sites.

The CI and SHEAR were corrected to an arbitrary value of $\theta_{gc} = 0.25$.

After correction, plot of the adjusted CI and SHEAR versus θ_g depicted in Fig. 3 shows no relationship between both strength parameters and θ_g ($P > 0.10$), which indicates that any changes in adjusted CI and SHEAR values are independent of θ_g changes and most probably due to treatment effects. This conclusion is also corroborated by the slight but significant differences in CI and SHEAR for the NAEW and NWAES sites in November and December, which were not adjusted because of non-significant differences in θ_g. Differences in CI and SHEAR values between T0 and T200 were still, however, significant, indicating that stover management affected the crust strength parameters independent of changes in θ_v. Results of ANOVA conducted on unadjusted and adjusted CI and SHEAR showed that adjustments greatly reduced the CI and SHEAR differences among treatments (Fig. 4 and 5). Adjusted results indicate that field θ_g can indeed significantly mask treatment differences in crust strength parameters. Unadjusted values of CI and SHEAR showed that stover treatment differences for CI and SHEAR were mostly large and highly significant at all sites when actually were not based on the adjusted CI and SHEAR (Fig. 4 and 5). For example, differences in unadjusted CI and SHEAR between T0 and T200 at NWAES were highly significant ($P > 0.001$), but the adjustment for θ_g reduced differences by 60 and 76% and the new differences were not significant ($P > 0.10$). Adjusted CI and SHEAR values are hereafter referred to as CI and

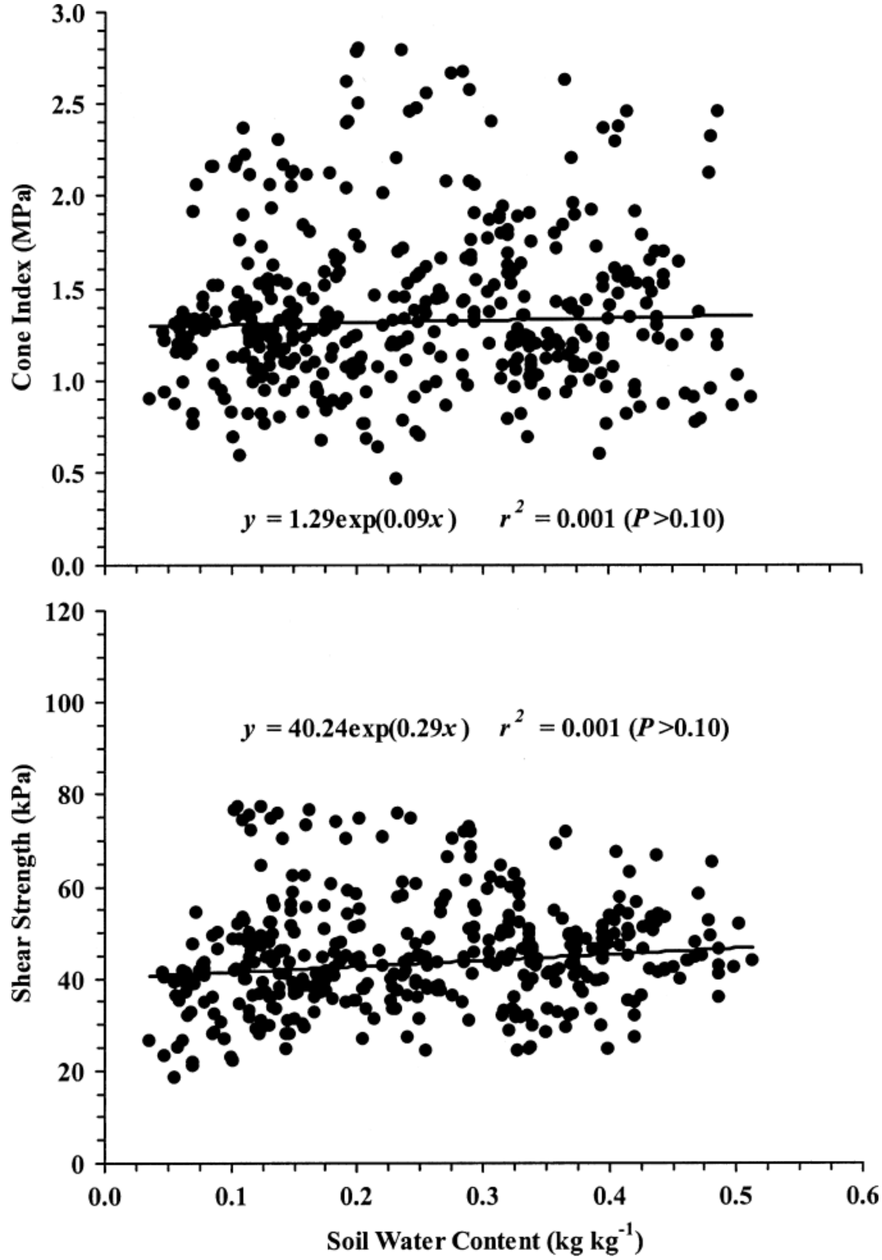

Fig. 3. Adjusted data of cone index and shear strength versus gravimetric water content for all data points across the three study sites.

SHEAR, and results are discussed based on the adjusted values only.

Stover Effects on Cone Index and Shear Strength

Removal of corn stover induced rapid changes in soil crust strength parameters ($P < 0.05$), but doubling the amount of stover left on the soil surface (T200) did not significantly affect crust strength parameters compared with the normal stover treatment (T100). Increased removal of stover from 0 to 5 Mg ha^{-1} resulted in higher CI and SHEAR, but the removal effects varied among sites in the order of NAEW > NWAES > WAES (Fig. 4 and 5). The greatest effect of stover removal occurred at the NAEW site where differences in CI and SHEAR were larger and more wide-spread than those at WAES and NWAES for each month. At this site, the CI for the T0 was higher by a factor of about 1.3 than T100 over the entire study period ($P < 0.01$). Similar pattern of differences was observed for SHEAR at the same site. The SHEAR under T0 was 1.2 of that in T100 except during the first month (June) where differences between T0 and T100 were not significant. In May 2005, at the end of the first year of stover management, the CI for T0 was 42% higher than that for T100 at NAEW ($P < 0.01$; Fig. 6). At the same site, SHEAR for T0 was 30% higher than that for T100 ($P < 0.01$; Fig. 7). While CI and SHEAR decreased quadratically with increasing stover cover, differences among T25, T50, T75, and T100 were not significant, indicating that complete removal of stover

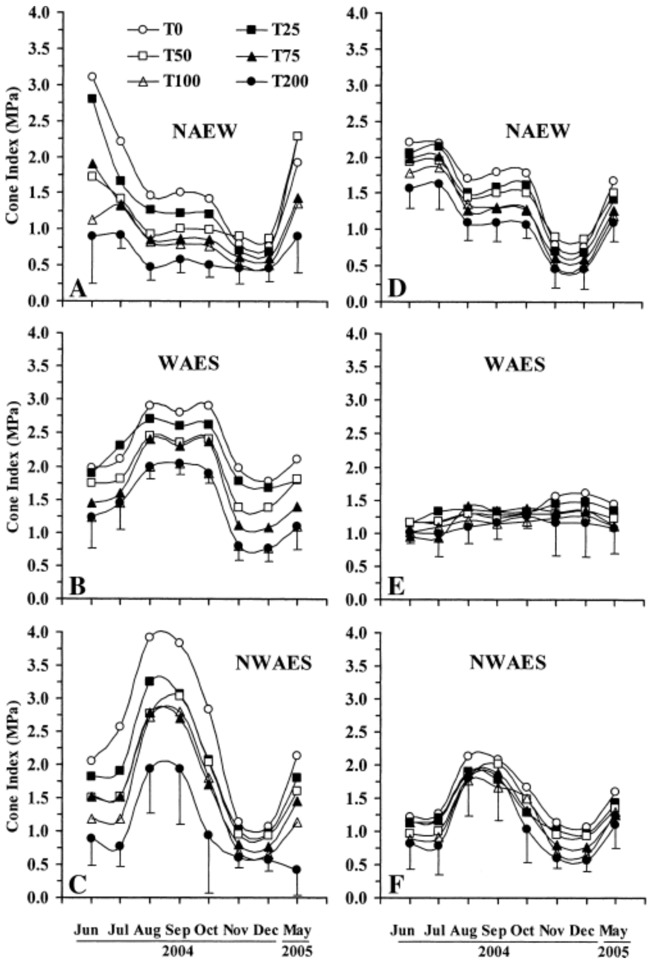

Fig. 4. Unadjusted (A, B, and C) and adjusted (D, E, and F) CI values for June through December 2004 and May 2005 for the North Appalachian Experimental Watersheds (NAEW), Western Agricultural Experiment Station (WAES), and Northwestern Agricultural Experiment Station (NWAES) in Ohio. The T0, T25, T50, T75, T100, and T200 are the six rates of corn stover at 0, 25, 50, 75, 100, and 200%, respectively. The error bars represent the LSD values by month.

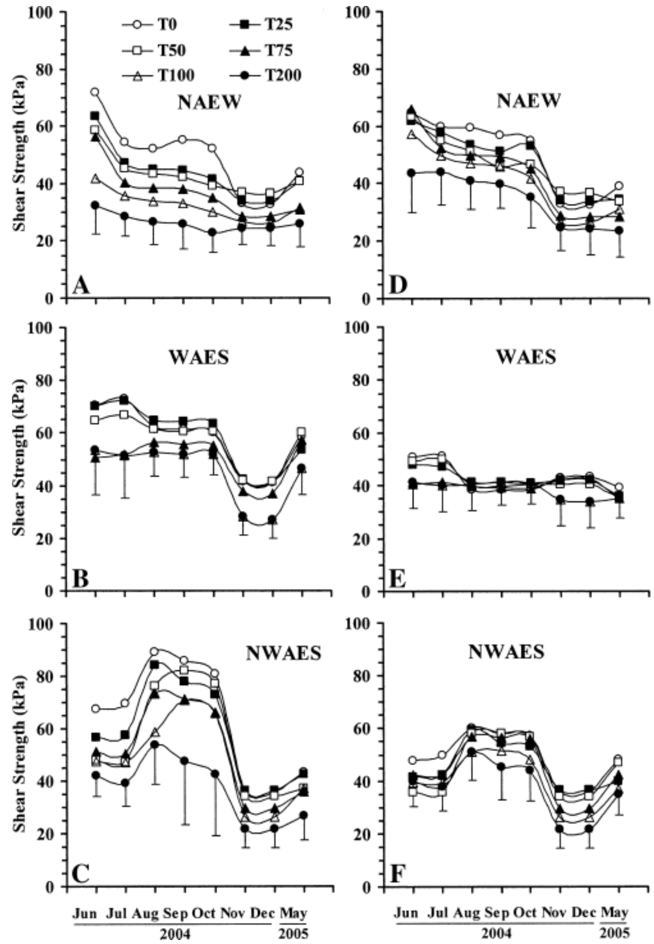

Fig. 5. Unadjusted (A, B, and C) and adjusted (D, E, and F) shear strength values for June through December, 2004, and May 2005 for the North Appalachian Experimental Watersheds (NAEW), Western Agricultural Experiment Station (WAES), and Northwestern Agricultural Experiment Station (NWAES) in Ohio. The T0, T25, T50, T75, T100, and T200 are the six rates of corn stover at 0, 25, 50, 75, 100, and 200%, respectively. The error bars represent the LSD values by month.

has a larger impact on increasing soil crust strength than partial removal of stover (Fig. 6 and 7).

At WAES, changes in CI and SHEAR were small and not significant for any month in contrast with those at NAEW (Fig. 4 and 5). One year after experiment commencement, CI increased quadratically and SHEAR linearly with increase in stover removal rates, but due to the large variability in data, differences were not significant (Fig. 6 and 7). This finding corroborates our hypothesis that the extent of impact of stover removal on crust strength properties can be site-specific. The sloping and unglaciated soils at NAEW apparently were more susceptible to changes in crust strength induced by stover removal as compared with glaciated and nearly flat (<2% slope) terrain at WAES. Other studies have also shown that the effectiveness of stover mulch in improving soil surface strength often varies among soils (Gupta et al., 1987).

Stover removal effects on crust strength parameters at NWAES were highly variable, and significant differences were only present after 5 mo of stover management where T100 slightly reduced CI and SHEAR compared with T0 ($P < 0.05$). At the same site, 1 yr after the onset of the experiment (May 2005), the CI under T100 was not significantly different from that under T0, but the SHEAR under T100 was slightly lower ($P < 0.05$). While the CI values, at this site, decreased quadratically (Fig. 6) with increasing rates of stover mulch, the large variability in CI data diminished any significant differences among stover treatments. The relatively smaller treatment effects on crust strength at NWAES as compared with those at NAEW may be due to differences in site conditions. Soils at NAEW are silt loam and unglaciated with steep slopes (>10% slopes) while those at NWAES are clay loam and are practically flat (<1%). Thus, results show that the effects of complete stover removal on crust strength of a glaciated clay loam may be slower than under unglaciated silt loam. In a study on glaciated soils in the midwest U.S. Corn Belt region, Gupta et al. (1987) observed that differences in

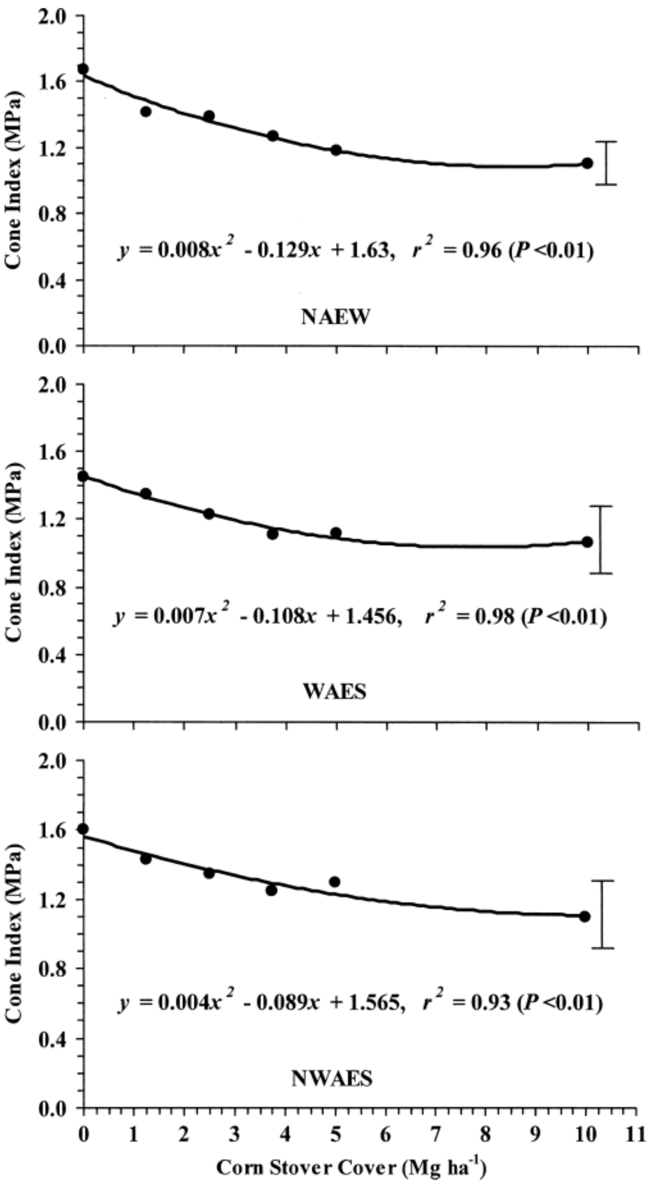

Fig. 6. Cone index measured at the end (May 2005) of the first year of stover management as a function of stover removal for the North Appalachian Experimental Watersheds (NAEW), Western Agricultural Experiment Station (WAES), and Northwestern Agricultural Experiment Station (NWAES) in Ohio. The error bar represents the LSD value.

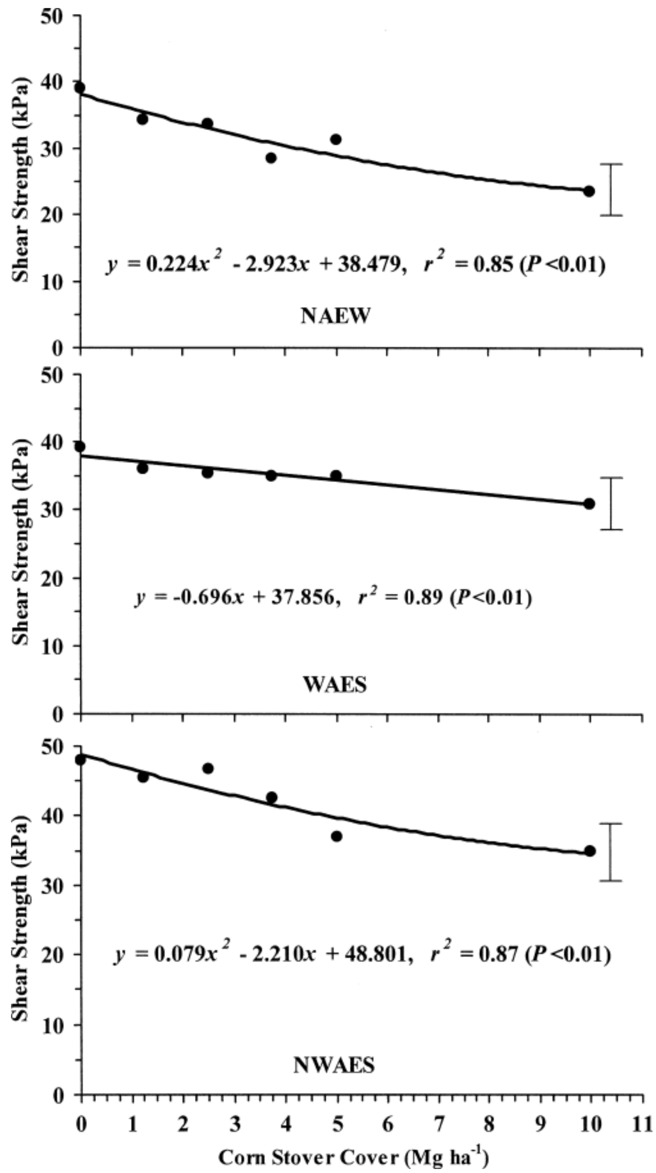

Fig. 7. Shear strength measured at the end (May 2005) of the first year of stover management as a function of stover removal for the North Appalachian Experimental Watersheds (NAEW), Western Agricultural Experiment Station (WAES), and Northwestern Agricultural Experiment Station (NWAES) in Ohio. The error bar represents the LSD value.

soil strength parameters after adding stover at 0.0, 3.4, 6.7, and 10.1 Mg ha^{-1} on Zimmerman sand, Sargent silt loam, and Webster clay loam were very small particularly on the soils with high clay content.

The rapid increase in soil strength with increase in rate of stover removal at NAEW agrees with the results reported by Guerif (1979). It contrasts, however, with the long-term studies of Karlen et al. (1994), who reported that complete removal of stover did not reduce the CI values in two sloping (>10% slope) silt loams in Wisconsin after 10 yr. Site interactions of soil-stover-tillage may be the reason for these controversies. In this study, soils under treatments with reduced stover cover exhibited visible aggregate breakdown/detachment, surface sealing, and crusting in the surface 3-cm depth due to the disruptive forces of raindrops that caused near-surface soil consolidation. Bare soils were more susceptible to rapid crust formation and cracking. Continuous and massive crusts with a thickness of 3 ± 0.7 cm and abundant cracks with a width of 0.6 ± 0.5 cm were observed under T0 and T25 treatments in dry months. Crusting and cracking also occurred in the remainder of the treatments but they were less extensive. Stover mulch cover also greatly altered the roughness of the soil surface. The soil surface below the stover mulch in T75, T100, and T200 was looser and had greater roughness than that in T0, T25, and T50 due to differential raindrop interception.

Because soil texture differences are not significant within each site, any significant differences in crust strength parameters are attributed solely to the effects of mulch cover. Slow decomposition of stover mulch left on the soil surface can have a greater effect on improving soil physical properties than that plowed or mixed with soil (Skidmore et al., 1986). Results show that benefits attributed to NT management for reducing crust strength properties would decrease rapidly in some soils if stover is removed. Dabney et al. (2004) reported that improvement in soil quality by long-term NT systems could be lost within 1 yr of complete mulch removal and adoption of fallow management. Thus, corn stover mulch is essential to reducing soil crust strength by protecting the soil from the combined effects of raindrop impact, excessive drying, surface sealing, and crusting (Kladivko, 1994). Data from this study show that excessive stover removal as biofuel or other purposes can exacerbate risks of soil crusting and increase crust strength, but the magnitude of effects will highly depend on site-specific conditions.

Stover Effects on Bulk Density

The soil ρ_b measured at the surface 0- to 6-cm depth was strongly affected by the stover treatments at all sites even within the short period of 1 yr ($P < 0.01$). The ρ_b increased when stover was removed, but it was unaffected when stover was added from T100 to T200. The extent of ρ_b increase with stover removal varied with site (Fig. 8), paralleling the response of CI and SHEAR to stover removal. On average, reductions in ρ_b with increasing stover retention from T0 to T100 were higher at NAEW (1.35 vs. 1.24 Mg m^{-3}) and NWAES (1.34 vs. 1.22 Mg m^{-3}) than at WAES (1.38 vs. 1.32 Mg m^{-3}) between June and December 2004. Two months after the imposition of the treatments, the ρ_b for the T0 and T25 was significantly higher than that for the rest of the treatments at NAEW and NWAES but not at WAES site (Fig. 8). The slow changes in ρ_b at the WAES site show that beneficial effects of stover mulch depend on soil type and land use history. In some soils, differences in ρ_b between bare and stover mulched soils cannot be measurable at short intervals because substantial decomposition and incorporation of stover into the soil may be necessary before changes in ρ_b are measurable (Skidmore et al., 1986; Kladivko, 1994; Schonbeck and Evanylo, 1998). The ρ_b for the T100 was significantly lower than that for the T0 throughout the year except in November and December for the WAES and NWAES sites. Increased soil wetness and early onset of freezing-thawing cycles of the near-surface soil may have diminished differences in ρ_b among treatments (Halvorson et al., 2003).

The ρ_b measured in May 2005, 1 yr after experiment initiation, decreased quadratically with the increase in stover retention rates at NAEW and WAES and linearly at NWAES (Fig. 9). At this time, ρ_b under T0 was 10% higher at NAEW, 13% at WAES, and 6% at NWAES than that under T100. Higher clay content of soils at NWAES probably reduced differences in ρ_b among treatments in accord with the small CI and SHEAR differences at this site. Trends of rapid changes in ρ_b by stover removal are in accord with those reported by Morachan et al. (1972) who observed that addition of corn stover and other crop residues reduced ρ_b and improved soil tilth on a Marshall silty clay loam. In a study with wheat (*Triticum aestivum* L.) straw, Black (1973b) showed that increase in retention of straw at 0, 25, 50, and 100% from the previous year decreased significantly the ρ_b on a Dooley sandy loam. Our results, however, are in contrast with those reported by Karlen et al. (1994) in a 10-yr study of NT corn systems when stover mulch was completely removed, doubled, and maintained in two silt loams in Wisconsin. In that study,

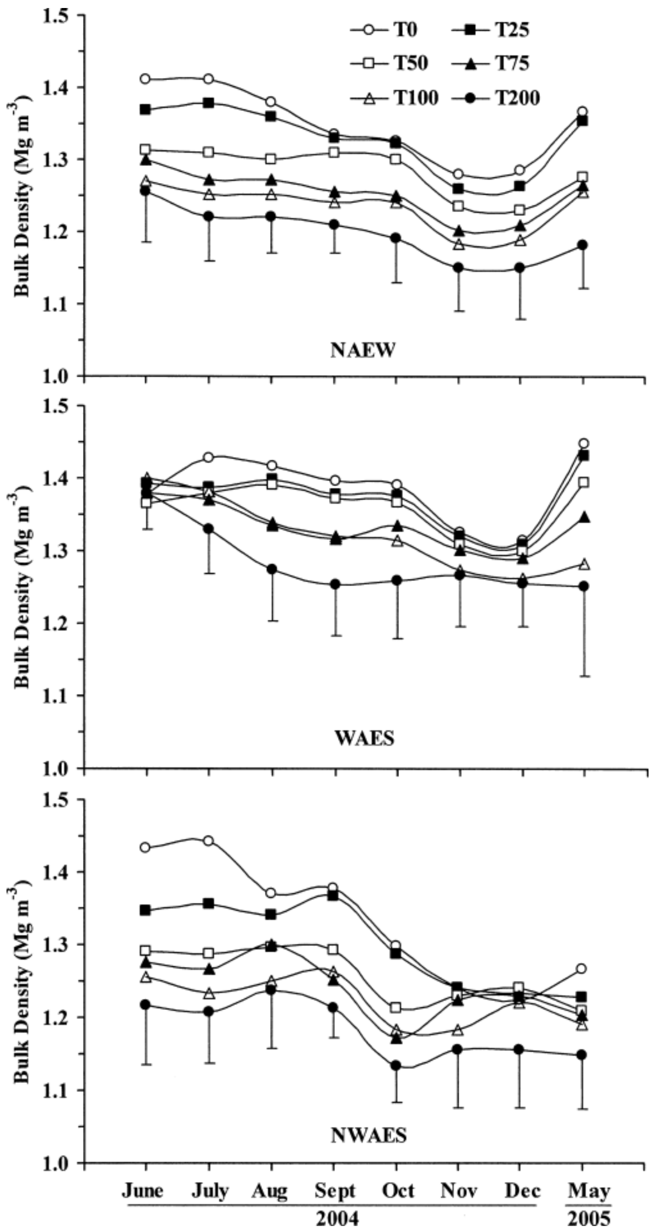

Fig. 8. Bulk density from June to December 2004 and May 2005 for the North Appalachian Experimental Watersheds (NAEW), Western Agricultural Experiment Station (WAES), and Northwestern Agricultural Experiment Station (NWAES) in Ohio. The T0, T25, T50, T75, T100, and T200 are the six rates of corn stover at 0, 25, 50, 75, 100, and 200%, respectively. The error bars represent the LSD values by month.

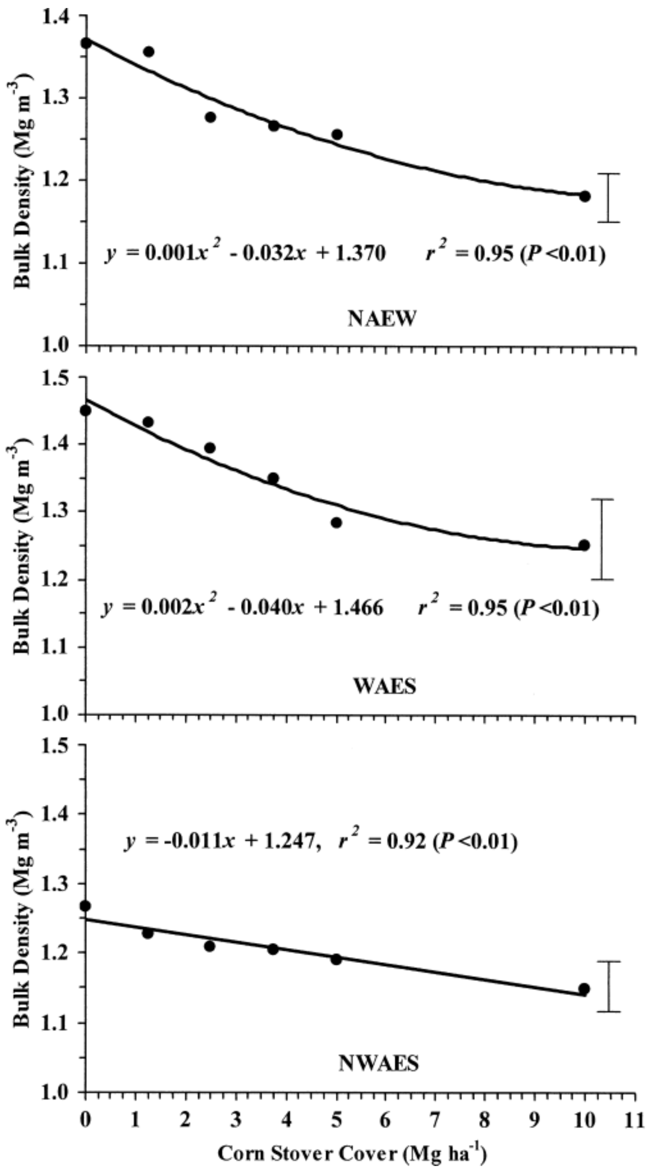

Fig. 9. Bulk density measured at the end (May 2005) of the first year of stover management as a function of stover removal for the North Appalachian Experimental Watersheds (NAEW), Western Agricultural Experiment Station (WAES), and Northwestern Agricultural Experiment Station (NWAES) in Ohio. The error bar represents the LSD value.

they concluded that high variability in ρ_b among treatments due to inherent soil characteristics reduced statistical differences. In some ecosystems, effects of residue removal on ρ_b are either small or noticeable only after several years of management (Kladivko, 1994). In this study, however, stover left on the soil surface reduced significantly the ρ_b within 1 yr.

These data indicate that the unincorporated stover mulch most likely reduced the ρ_b by protecting the soil surface from the external agents (i.e., raindrop impact) causing consolidation and densification of the surface layers. Corn stover mulch buffers the soil surface against external forces and reduces detachment and rapid wetting and drying of the soil (Karlen et al., 1994; Wilhelm et al., 2004). Although no actual counts were made, field observations at the three sites showed that stover mulched plots had higher number of earthworms (*Lumbricus terrestris* L.) and biopores than nonmulched plots, which probably explains the large reduction in ρ_b in mulched plots. These visual observations are corroborated by previous studies at these long-term NT sites showing abundant surface-dwelling earthworms as compared with residue-free systems (Bohlen et al., 1997; Butt et al., 1999). Increases in soil-water content with mulching may also be another factor for decreasing ρ_b (Dianqing et al., 2004).

Results at the end of the first study year show that differences in ρ_b between T0 and T25 were not significant at NAEW and WAES. While there was a progressive decrease in ρ_b with increase in stover retention, there were no significant differences in ρ_b between T75 and T100 at the three sites. These results imply that removal of 25% of corn stover may not significantly alter ρ_b in these soils. Further, long-term assessment of ρ_b is, however, needed to ascertain the thresholds levels of stover removal for these soils accounting for seasonal variations in ρ_b.

The correlation of CI and SHEAR with ρ_b was small. This independence among parameters is consistent with the findings by Grunwald et al. (2001), who showed that CI might not always be significantly related to ρ_b. The correlations of unadjusted CI and SHEAR with ρ_b were, however, stronger but varied significantly among locations (Fig. 10; $P < 0.01$). They were highly significant for the NAEW site followed by NWAES but not significant for the WAES site ($P > 0.10$). The unadjusted CI increased linearly with increase in ρ_b at NAEW and NWAES sites. The ρ_b explained 44% of variability in unadjusted CI at NAEW and 34% at NWAES, while it explained 55% of variability of unadjusted SHEAR at NAEW, 28% at NWAES, and 26% at WAES, indicating that ρ_b was a better predictor of SHEAR at NAEW than at other sites ($P < 0.01$; Fig. 11). Relationships of CI and SHEAR with ρ_b were a function of soil water content.

Stover Effects on Volumetric Water Content

The impact of stover management on θ_v was more consistent and more pronounced than that on CI and SHEAR. The θ_v decreased with systematic removal of corn stover except during winter months ($P < 0.01$; Fig. 12). At NAEW, the θ_v for the T100 averaged across sampling dates from June to October (0.47 mm^3 mm^{-3}) was higher by a factor of 1.2 than that for the T0 (0.38 mm^3 mm^{-3}) and T25 (0.39 mm^3 mm^{-3}). At NWAES and WAES, the θ_v for the T100 averaged from June 2004 to May 2005 was higher by a factor of 1.7 than that for the T0 and 1.5 than that for the T25. The lowest θ_v was observed for the T0 and the highest for the T200. Differences in θ_v between T75 and T100 were not significant at any site, suggesting that removal of 1.25 Mg ha^{-1} of stover, as biofuel, may not negatively affect θ_v. Stover removal did not affect the θ_v during the sampling dates in November and December. Increase in θ_v with the onset of winter months most likely eliminated treatment effects. The large impacts of stover removal on reducing θ_v are in accord with Sharratt (2002) who showed that stover removal

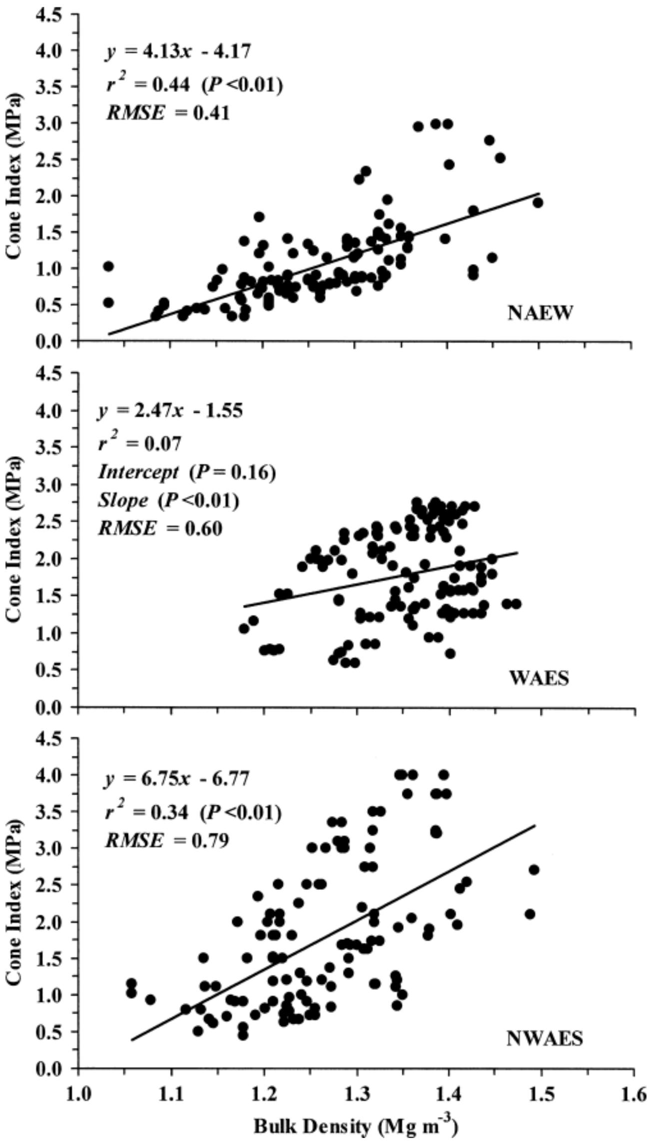

Fig. 10. Relationship between cone index and bulk density across treatments and months in response to stover removal under no-till continuous corn management for the three research sites.

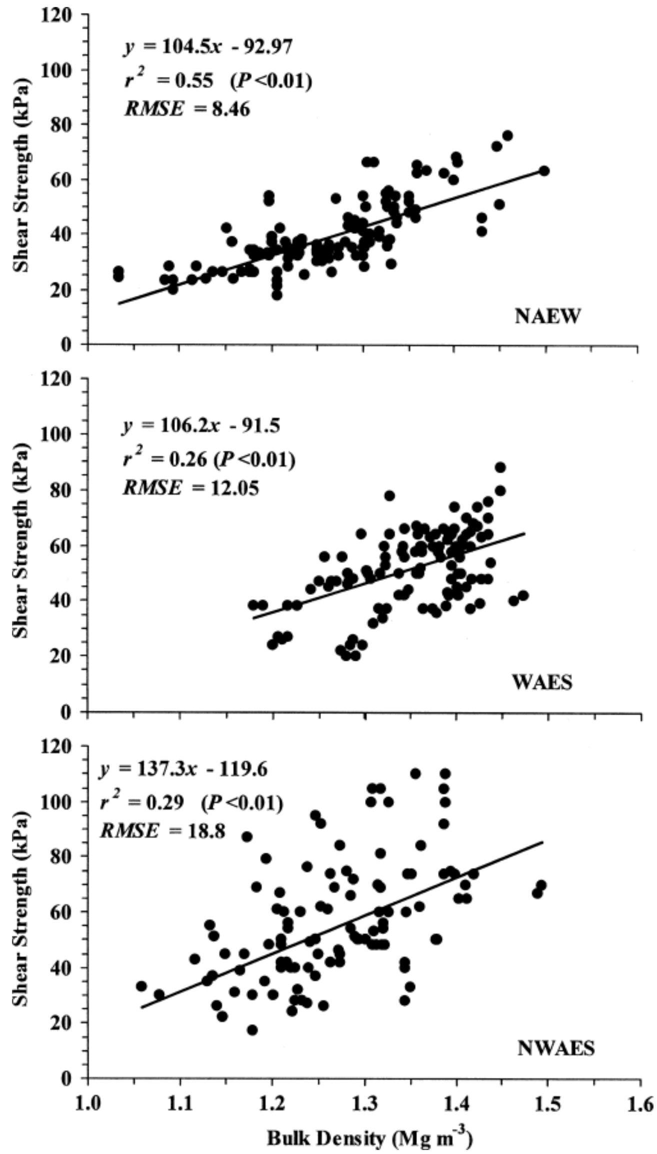

Fig. 11. Relationship between shear strength and bulk density across treatments and months in response to stover removal under no-till continuous corn management for the three research sites.

reduced the θ_v. High θ_v, under high rates of stover mulch, is attributed to improved water-holding capacity of the soil and reduction in both evaporation rates and abrupt fluctuations in soil temperature (Black, 1973a).

Impact of stover removal on θ_v was rather rapid and differences were detectable even within approximately 1 mo of imposing the treatment unlike the small differences in ρ_b, CI, and SHEAR. In May 2005, 1 yr after experiment initiation, the θ_v increased quadratically with increase in rate of stover retention at NAEW and WAES and linearly at NWAES ($P < 0.01$; Fig. 13). The quantity of stover retained explained 97% of the variability in θ_v at NAEW, 90% at WAES, and 95% at NWAES, showing that the magnitude of stover retention controls the soil water dynamics. Other studies have also found high correlation between stover removal and θ_v. Wilhelm et al. (1986) observed that stover removal explained 84% of variations in soil water storage in NT systems on a Crete-Butler silty clay loam. In May 2005, differences in θ_v between T100 and T75 at NAEW and NWAES were not significant, which shows that the removal of 1.25 Mg ha^{-1} (25%) of stover may not significantly affect the θ_v in these soils. Figure 12 shows that θ_v among T0, T25, and T50 were about the same at WAES and NWAES, indicating that the stover left on the soil surface in these treatments the year before may have mostly decomposed, reducing the protective mulch cover against evaporation. After 1 yr, the θ_v increased with doubling the amount of stover left on the soil surface compared with the normal stover treatment ($P < 0.01$; Fig. 12). The T200 increased θ_v by 1.3 times at NAEW and WAES and 1.6 times at NWAES compared with T100 ($P < 0.05$), which indicates that high addition (5 Mg ha^{-1}) of stover maintained the protective cover and reduced evaporation more than the normal stover treatment after 1 yr. Overall, removal or addition of corn stover rapidly changes the θ_v,

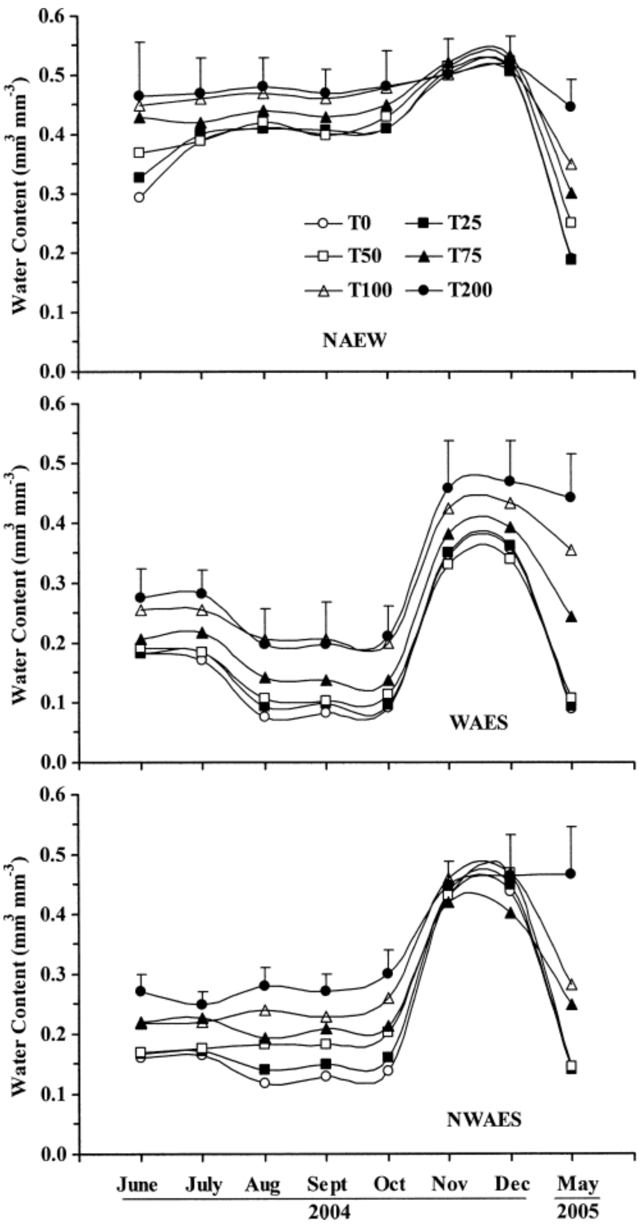

Fig. 12. Volumetric water content from June to December 2004 and May 2005 for the North Appalachian Experimental Watersheds (NAEW), Western Agricultural Experiment Station (WAES), and Northwestern Agricultural Experiment Station (NWAES) in Ohio. The T0, T25, T50, T75, T100, and T200 are the six rates of corn stover at 0, 25, 50, 75, 100, and 200%, respectively. The error bars represent the LSD values by month.

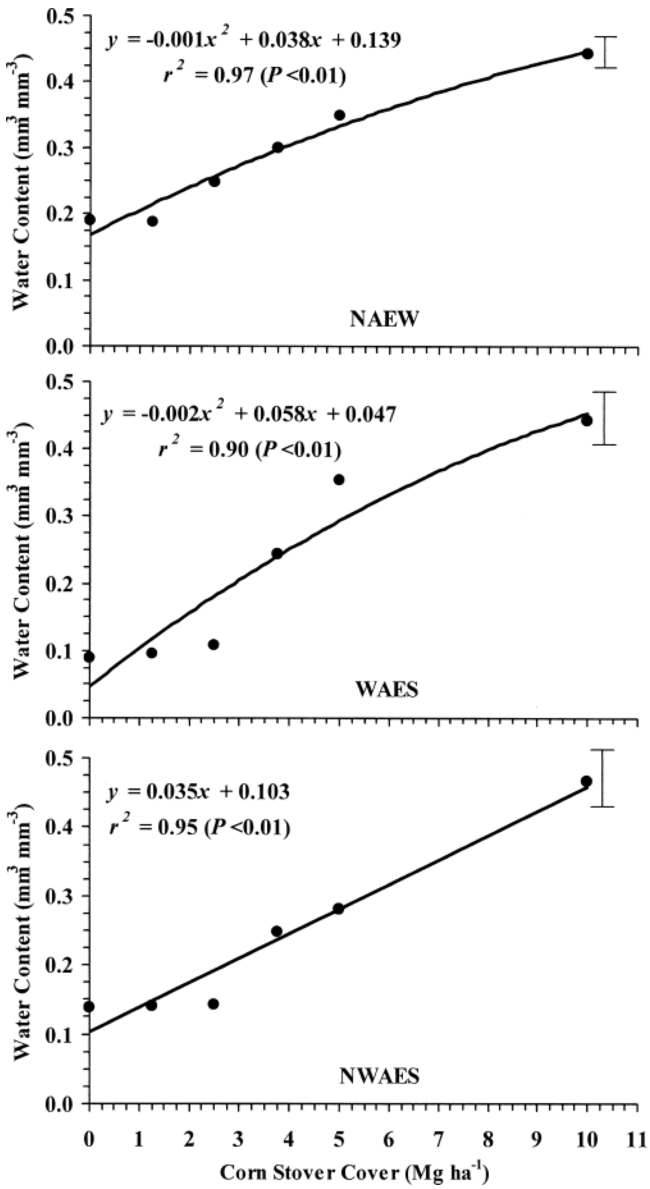

Fig. 13. Volumetric water content measured at the end (May 2005) of the first year of stover management as a function of stover removal for the North Appalachian Experimental Watersheds (NAEW), Western Agricultural Experiment Station (WAES), and Northwestern Agricultural Experiment Station (NWAES) in Ohio. The error bar represents the LSD value.

and the magnitude and rate of θ_v changes were greater than those of CI and SHEAR.

CONCLUSIONS

Our study shows that removal of corn stover as biofuel can induce rapid and significant changes in soil crust strength properties and water content in NT continuous corn systems across three Ohio soils even within a 1-yr period. The magnitude of changes in crust strength parameters is, however, a site-specific function of soil type and ecosystem. At the end of the first year following stover removal, complete removal of stover increases the CI significantly in unglaciated soils. In contrast, changes in CI and SHEAR resulting from stover removal in glaciated soils are small. Apparently, stover removal effects on glaciated soils with relatively high clay content are slower than those on unglaciated and sloping soils. The consistent effect of removing stover is on increasing bulk density and reducing the water content across soils. Soils with all stover removed are much drier, denser, and less porous than soils with stover retained, thereby increasing the crust strength. Differences in bulk density and soil water content between soils with all stover maintained and soils with 25% (1.25 Mg ha^{-1}) of stover removed were not generally significant, which shows that removal of 1.25 Mg ha^{-1} of stover for biofuel production or other uses from NT soils may not negatively affect these soil properties. Compared with normal stover treatments, doubling the amount of stover left on the soil surface increases soil water content but its effects on crust strength properties and bulk density are negligible. The small differences in CI and shear strength among stover treatments underscore the need for long-term monitoring of soil crust strength properties to define threshold levels of stover that can be removed safely without affecting the soil physical properties.

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